ON THE AMPACITY OF INSULATED CONDUCTORS IN CONDUIT

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Abstract – **In the paper, a practical method for determining the smallest allowable cross-sectional area of circuit insulated conductors or single-core cables in conduit buried in a thermally insulated wall is proposed. A way to obtain a simple formula for aluminum or copper conductors is described and a formula based on the Romanian norm I7-2002 is given. It can be used for easy cross-section evaluation.**

Keywords: *ampacity, insulated conductors and cables in conduit.*

1. INTRODUCTION

It is well known that the current-carrying capacities of conductors depends on the steady state maximum admissible temperature supported by the used insulating materials, on the external temperature, on cooling surface and on the equivalent coefficient of thermal transfer. The equivalent coefficient of thermal transfer α is in general difficult to evaluate, because it depends on the cooling surface shape, thermal conductivity of insulating materials, geometrical dimensions and set up. This is why we used the data given for various norms, well verified in long practice to evaluate the product of equivalent heat transfer coefficient and the equivalent cooling surface.

2. CONDUCTOR TEMPERATURE

2.1. Evaluation of cooling surface

We will consider the conductor cross-section not round but a square with the side a. In this case the cross-section area of a package of n conductors with s cross section area, (n - perfect square), will have the following total area and external perimeter:

$$S = n\,s = n\,a^2, \quad p = 4\,a\sqrt{n} \tag{1}$$

So, extending this propriety to all the integers, the external cooling area per unit length of a group of n parallel s-cross-section conductors can be considered approximately equal to:

$$S_c \cong 4\sqrt{s\,n} \tag{2}$$

Due to relatively small cross-section of conductors, in steady state, the temperature θ_m can be considered uniform distributed in conductor cross-sections and in all the conductors of the package. For the same current I in all the (identical) conductors, the difference between this temperature and the external temperature θ_0 can be determines as follows [1], [5]:

$$\theta = \theta_m - \theta_0 = \frac{\rho I^2 n}{\alpha\, s\, S_c} \quad [\mathrm{K}] \tag{3}$$

Where ρ is the conductor material resistivity at temperature θ_m.
Replacing S_c from (2) we obtain:

$$\theta = \theta_m - \theta_0 = \frac{\rho I^2 \sqrt{n}}{4\alpha\, s^{1.5}} \quad [\mathrm{K}] \tag{4}$$

The heat transfer coefficient α has two components: convection heat transfer coefficient and radiation heat transfer coefficient, proportional with the 3-th power of the absolute temperature. In our case, at relatively low temperatures, dominant is the convection heat transfer coefficient. This coefficient decreases with the 1 to 0.25 power of characteristic length [1], [4]. For simplicity reason we will assume that it decreases with 0.5 power of the conductor thickness:

$$\alpha = \frac{\alpha_0}{\sqrt[4]{s}} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}}\right] \tag{5}$$

Replacing in (4) this coefficient the following expression is obtained for the temperature growth in current carrying conductors:

$$\theta = \frac{\rho I^2 \sqrt{n}}{4\alpha_0\, s^{1.25}} \quad [\mathrm{K}] \tag{6}$$

It results for the maximum admissible current:

$$I = 2\sqrt{\alpha_0 \frac{\theta}{\rho} \frac{s^{1.25}}{\sqrt{n}}} \quad [\mathrm{A}] \tag{7}$$

3. HEAT TRANSFER COEFFICIENT

The heat transfer coefficient α_0 will be determined to fit the maximum admissible currents given in I7 norm from 2002 [3]. In the new norm from 2009, the maximum admissible currents for conductors in conduit are not given and the use of given by conductor producer ratings is recommended.

In fig. 1 the current-carrying capacities of PVC or rubber insulated conductors in conduit are given according to I7-2002 [3], [6].

$Cu^T =$

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	1	1.5	2.5	4	6	10	16	25	35	50	70	95	120	150
1	14	17	24	31	40	55	73	100	125	150	200	241	272	310
2	12	14	20	26	34	49	64	84	108	135	171	218	250	280
3	11	13	18	24	31	45	58	76	98	123	156	198	228	255
4	10	11	16	21	27	39	51	67	87	109	137	174	196	224

$Al^T =$

	0	1	2	3	4	5	6	7	8	9	10	11
0	2.5	4	6	10	16	25	35	50	70	95	120	150
1	18	23	30	41	55	74	95	118	155	187	217	238
2	16	20	27	38	47	66	83	103	131	166	191	214
3	15	18	25	33	43	60	76	94	119	151	174	195
4	13	16	21	29	38	53	65	82	104	133	153	171

Fig. 1 Cu and Al ampacities for 60° C and 25° C ambient (I7-2002): 0 rows: conductor cross section [mm^2]; 1-4 rows: current-carrying capacities in [A] for 2, 3, 4 and 5 or 6 conductors in conduit.

For the evaluation of the equivalent heat transfer coefficient on the surface of the conductor, the values of admissible currents (fig. 1) was used to determine the quantity α_0 with the equation:

$$\alpha_0 = \frac{\rho I^2 \sqrt{n}}{4\theta s^{1.25}}\ ; \quad \left[\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}\right] \tag{8}$$

The results are presented in fig. 2 and 3 and the mean values of α_0 and their constant of variation for copper and aluminum are given in table 1. The electrical conductivity was considered as in table 1.

Table 1

	Unit	Cu		Al	
$\sigma = 1/\rho$ at 20°C	MS/m	59.5		37.7	
Mean α_0 and its variability ratio for n = 2	$\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}$	1.135	5.8 %	1.037	8.9 %
Mean α_0 and its variability ratio for n = 3	$\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}$	1.049	9.5 %	0.989	8.6 %
Mean α_0 and its variability ratio for n = 4	$\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}$	1.008	9.3 %	0.946	9.2 %
Mean α_0 and its variability ratio for n = 6	$\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}$	0.952	10.1 %	0.884	9.3 %
Overall mean α_0 and its variability ratio	$\frac{\mathrm{W}}{\mathrm{m}^{1.5}\mathrm{K}}$	**1.036**	**10.8 %**	**0.964**	**10.7 %**

It can be seen in fig. 2 and 3, as well as in table 1, that despite the scatter of data, they are almost the same for all the cross section area. Also the average values are enough close to each other and for both materials the value of α_0 can be considered equal to 1.

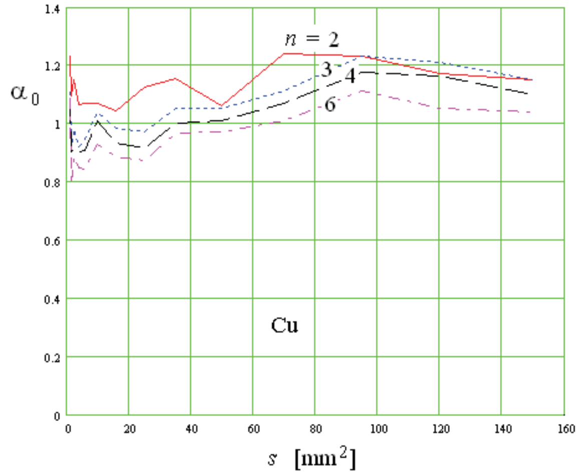


Fig. 2 Values of α_0 determined from the ampacity of copper conductors for 2 up to 5 of them loaded versus wire cross section

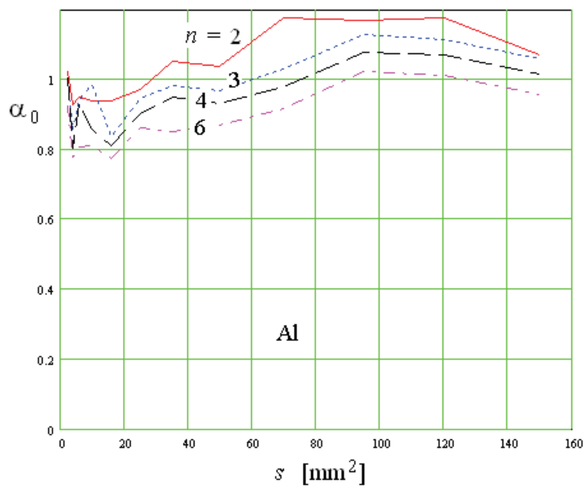


Fig. 3 Values of α_0 determined from the ampacity of Al conductors for 2 up to 5 of them loaded versus wire cross section

The equivalent heat transfer coefficient α increases several times for small conductor cross-sections and is about 7% smaller for aluminum conductors (fig. 4).

4. AMPACITY OF CONDUCTOR IN CONDUIT

Taking into account that we can consider $\alpha_0 = 1$ W/(m$^{1.5}$K), a general approximate formula can be proposed for the conductor current-carrying capacity evaluation, issuing from (7):

$$I = 2\sqrt{\frac{\theta}{\rho}\frac{s^{1.25}}{\sqrt{n}}} \quad [\mathrm{A}]; \quad s\,[\mathrm{m}^2],\ \rho\,[\Omega\,\mathrm{m}] \tag{9}$$

It can be seen that in general, the ampacity is proportional to the square root of difference of temperatures of conductor and ambient and inversely proportional to the number of loaded conductors in the conduit at 0.25 power. The ampacity of aluminum conductors is almost 80% from the copper conductors with the same cross-section and insulation [2].

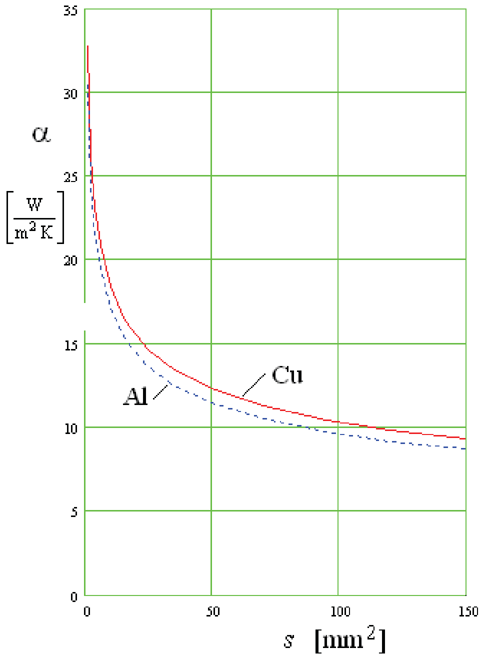
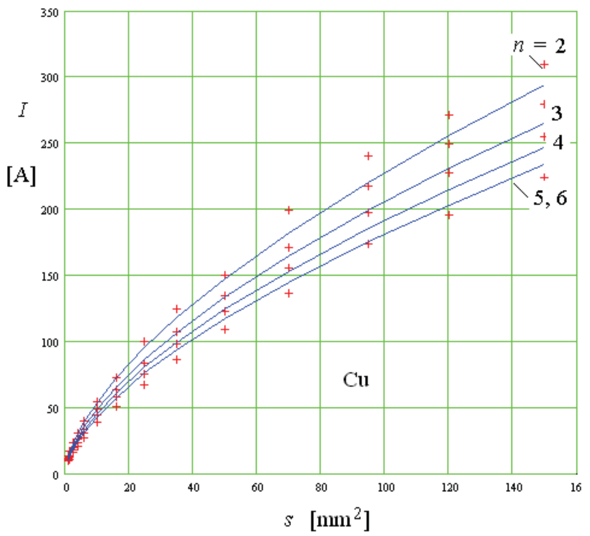


Fig. 4. Heat transfer coefficient versus wire cross section

More practical, if the conductor cross section is taken in mm^2 and the wire conductivity $\sigma = 1/\rho$ in MS/m, the equation (9) becomes:

$$I = 0.356\sqrt{\sigma\theta\frac{s^{1.25}}{\sqrt{n}}}\ \text{[A]};\quad s\,[\text{mm}^2],\ \sigma\,[\text{MS/m}] \qquad (10)$$



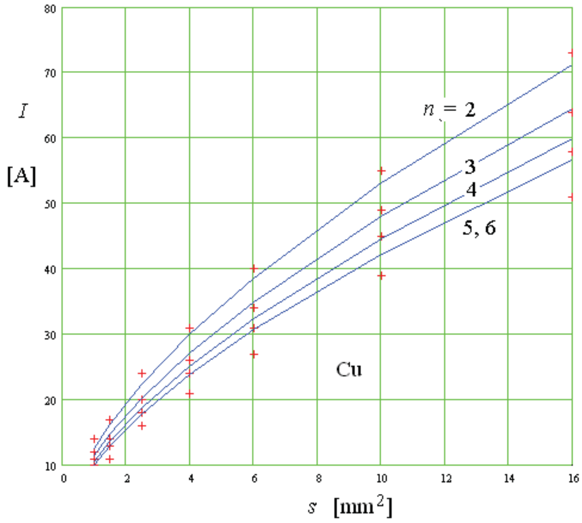


Fig. 5. Ampacities of copper insulating conductors in conduit, calculated with formula (solid line) and I7-2002 (points)

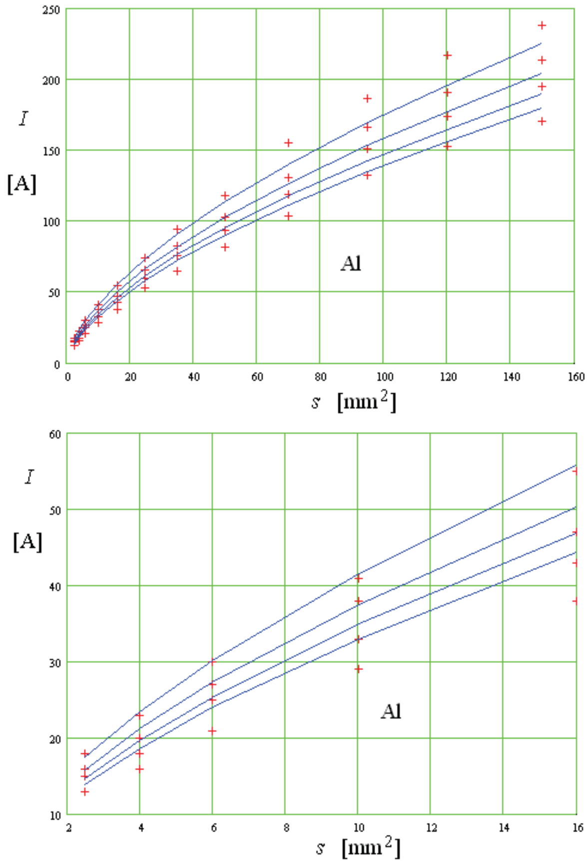


Fig. 6. Ampacities of aluminum insulating conductors in conduit, calculated with formula (solid line) and I7-2002 (points)

4.1. Errors

The relative differences between the values of admissible currents given in I7-2002 and calculated with formula (7) and α_0 from table 1 are given in fig.

7. It can be seen that for 2 to 4 conductors in conduit almost all the errors are smaller than ~10%. Only for 5 or 6 loaded conductors the error are up to 16%.

ErCu = (%)

	0	1	2	3
0	9.108	3.498	1.948	-2.003
1	2.83	-6.282	-6.487	-16.334
2	5.494	-2.71	-5.91	-11.566
3	1.579	-5.716	-6.479	-13.474
4	1.729	-4.306	-6.243	-13.656
5	1.646	0.218	-1.1	-9.369
6	0.572	-2.421	-4.975	-11.65
7	4.235	-3.101	-5.792	-12.184
8	5.583	0.956	-1.561	-7.596
9	1.382	0.978	-1.137	-7.363
10	9.54	3.648	1.607	-5.649
11	9.061	9.177	6.555	-0.989
12	6.367	8.194	6.031	-3.621
13	5.447	5.403	3.15	-4.192

ErAl= (%)

	0	1	2	3
0	3.044	1.366	2.117	-6.421
1	-1.847	-5.545	-8.651	-14.142
2	-0.634	-1.03	-1.528	-12.538
3	-1.316	1.22	-5.543	-12.23
4	-1.315	-6.673	-8.249	-14.266
5	0.457	-0.845	-3.137	-9.529
6	4.506	1.046	-0.576	-10.088
7	3.869	0.338	-1.601	-9.238
8	10.562	3.412	0.944	-6.719
9	10.211	8.272	5.832	-1.435
10	10.518	7.654	5.385	-2.017
11	5.434	4.916	2.73	-4.746

Fig. 7. Differences between the given in I7 ampacities and calculated with (7), reported to the calculated ones. First column – 2 conductors, second – 3, third – 4, last column 5 or 6 conductors.

5. CONCLUSIONS

1. The performed analysis shows that the given in [3] ampacities (fig. 1) are not so exact, because the curves related to the heat transfer coefficient, resulting from them, are not monotone (fig 2 and 3) and the obtained values has up to 10% variability.
2. The similar analysis, made for the new edition of the norm I7 (2009) and IEC standard [2], [7] for cables, shows a monotone curves of the parameter α_0 and much smaller variability of the values.
3. The equations (7) and (9), obtained from average values of heat transfer parameters, with some simplified assumptions can be used for a rough evaluation of current-carrying capacity of a large range of conductors or cables from various materials.
4. Such evaluations can be useful in emergency conditions, in particular for quick identification of electrical causes of fires or explosions in buildings or factories realized on the basis of old materials and norms, like analyzed norm [3].
5. For 5 and 6 loaded conductors in the conduit the errors given by proposed formulas are larger and the given in [3] ampacities are smaller with up to 10% than calculated with formula (7).

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